N64-17674

NASA CR 53947

# MEASUREMENTS OF LIQUID NATURAL FREQUENCIES AND DAMPING IN COMPARTMENTED CYLINDRICAL TANKS


BY

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OTS PRICE

XEROX $

MICROFILM $


TECHNICAL REPORT NO 8

CONTRACT NO NAS8-1555

SwRI PROJECT NO 6-1072-2


PREPARED FOR

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
GEORGE C MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

5 FEBRUARY 1964


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(NASA CR - ; OTS: )

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ABSTRACT

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This report presents experimental resonant frequencies and damping ratios for 45°, 60°, and 90° compartmented tanks. These are presented for various sector wall configurations and translational excitation amplitudes.

Author

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## LIST OF SYMBOLS

| | |
|---|---|
| $a$ | Longitudinal acceleration of tank |
| $d$ | Cylindrical tank diameter |
| $d_h$ | Perforation hole diameter |
| $h$ | Liquid depth to bottom of tank |
| $x_o$ | Tank excitation amplitude in translation |
| $\omega^2 d/a$ | Dimensionless frequency parameter |
| $\gamma_s$ | Damping ratio |

# INTRODUCTION

The increasing demand for large missiles has inherently brought with it an increased demand for tanks with greater capacities of fuel and oxidizer. Clustering the tanks has provided this necessary capacity and, in so doing, has resulted in a comparably higher liquid slosh resonant frequency than found in a single tank for a missile with the same fineness ratio. This increase in slosh resonant frequency is generally desirable in that it keeps the liquid sloshing resonant and bending forces from coupling with the automatic control system and structural modes. Compartmenting a single tank also results in this added advantage.

This report gives the liquid slosh resonant frequencies and damping ratios that can be attained by compartmenting a cylindrical tank. It is also intended to show the increase in damping ratio which can be attained by the use of perforated sector walls, together with their limitations.

## TANK CONFIGURATIONS

Three compartmented flat-bottom cylindrical tanks are considered in this report - the tanks being compartmented into equal sectors of 45°, 60°, and 90°. The vertical sector walls extend from well above the liquid surface to the tank bottom. Several wall materials are considered, varying from solid to perforated stocks of different hole diameter perforations and percent openings. The tests were conducted under a gravity axial acceleration field and at a liquid depth equal to the tank diameter ($h/d = 1$).

In all cases, the tank was force excited through a frequency range which included the two lower resonant frequencies (1, 2)*. The direction of translational excitation relative to the sector walls is as shown in Figure 1. All the tests were conducted for three values of translational excitation amplitude ($x_o/d$), using the same facility and methods employed in (3).

*Numbers in parenthesis refer to the References given at the end of this report.

# LIQUID RESONANT FREQUENCIES

Computation of the liquid natural frequencies for sectored cylindrical tanks has been carried out as presented in (1); however, the effect of translational excitation amplitude on the natural frequencies cannot be accounted for in the computations, and it is this excitation amplitude which causes a significant difference between the theoretical and experimental natural frequencies. Previous exploratory experiments in compartmented cylindrical (1, 2) and in spherical tanks (4) have indicated that the theoretical natural frequencies can be approached only for small values of excitation amplitude ($x_o/d \leqq 0.00187$); for values greater than this, a significant decrease in natural frequencies exists with increase in excitation amplitude.

The liquid natural frequencies presented in this paper are the lowest resonant frequencies measured for the 45°, 60° and 90° compartmented tanks undergoing translational excitation. Figure 2 shows the theoretical natural frequencies and the experimental resonant frequencies versus translational excitation amplitudes for sector tanks of solid wall configuration. The theoretical natural frequencies are shown at $x_o/d = 0$. It can be seen from the results presented that the predicted natural frequencies are approached only at the reduced values of translational excitation.

Because of the complexity of the liquid sloshing in sector tanks with perforated walls, several figures are presented to illustrate the nonlinearities that exist. Figures 3, 4 and 5 show the results obtained with water as the test liquid and a translational excitation amplitude of $x_o/d = 0.00417$. The three-dimensional plots which follow in the remaining figures represent the change in resonant frequency versus the hole size and percent of sector wall perforation in the 45°, 60° and 90° sector tanks, respectively. The liquid resonant frequency in perforated sector tanks is largely affected by the amplitude of translation, more so in fact, because of the intermixing of liquids from one sector to another. To account for the flow of liquids through the perforations, tests were also conducted using methylene chloride as the test liquid. The lower viscosity apparently increases the liquid flow through perforations with considerable effect on the resonant frequencies.

Perforated baffles are widely used for liquid damping (5), but their effect on the natural frequency can be more detrimental than the advantages gained from damping. The decrease in resonant frequency can be noted in Figures 3, 4 and 5 for an increase in perforated hole size and percent of open area. Because of the complexity of the test results, various means of presenting the data were studied with the best results obtained by plotting the dimensionless resonant frequency parameter ($\omega^2 d/a$) versus an equivalent Reynolds number* based on perforation hole size and translational excitation amplitude.

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*The numerical values of the Reynolds numbers presented in (2) have been found to be in error and should be disregarded.

The results of these tests are presented in Figures 6, 7 and 8. Figure 6 presents the results for a 45° sector tank having perforated sector walls of 23 percent and 30 percent open areas. It can be seen from these results that the value of resonant frequency can be maintained equal to or greater than that of solid wall sectors up to a Reynolds number of 50,000 for the 23% open area sector wall, and to a Reynolds number of 20,000 for the 30% open area sector wall. Above these Reynolds numbers, the resonant frequencies drop to values corresponding to experimental resonant frequencies for an uncompartmented cylindrical tank.

Figure 7 presents the results for the perforated wall 60° sector tanks. The value of the resonant frequency corresponding to the solid sector wall is seen to exist up to a Reynolds number of about 9,000 for the 23% perforated wall, and t a Reynolds number less than 4,000 for the 30% open area sector wall. The corresponding plot for the 90° perforated wall sector tanks are presented in Figure 8. The resonant frequency of the 23% and 30% open area sector wall tanks agrees with the solid sector resonant frequency to a Reynolds number equal to 24,000; above this Reynolds number, the frequency drops off to a value corresponding to the uncompartmented cylindrical tank.

# LIQUID DAMPING

## Solid Walls

The damping of liquid sloshing at the resonant frequency for the 45°, 60°, and 90°, solid wall compartmented cylindrical tanks is low, averaging approximately 0.04. However, at frequencies below the resonant value, the liquid sloshing is effectively damped.

## Perforated Sector Walls

Because of the relatively low damping produced by solid wall compartmentation, an experimental test program was conducted using various perforated materials as the dividing wall partitions. Tests were conducted with perforated hole sizes varying from 0.020 in. to 0.079 in. and of various percent of open area, ranging from 8 to 30%. Test results obtained indicated a large nonlinear effect on liquid resonant frequency and damping ratio. The liquid viscosity and excitation amplitude have as large an effect on the liquid resonant frequencies and damping ratios as do the perforated hole size and percent of open area.

In general, the results obtained indicate that perforated partitions with less than 10% open area will increase the damping ratio to approximately 0.1, while maintaining a liquid resonant frequency corresponding to a solid wall compartmented tank. For partitions with open areas greater than 10%, the damping produced is greater than 0.10, but the corresponding liquid resonant frequencies approach that of an uncompartmented cylindrical tank.

Attempts to present the damping ratios vs Reynolds number, or other various parameters which include the factors affecting the damping, failed to yield an effective picture of this complex data. The best that could be done is something such as that shown in Figure 9 which is a three-dimensional plot of the damping ratio vs the dimensionless resonant frequency parameter, $\omega^2 d/a$, and the percentage of open sector area for a 45° sectored tank. The results presented are for three values of excitation amplitude, $x_o/d$, with water and methylene chloride as the test liquid. From these results, it can be seen that the maximum damping is produced for sectors with open areas of 16 to 23%. However, the excitation amplitude must be quite large to maintain the resonant frequency corresponding to solid sector walls. Additional tests with sectors of smaller hole ratios ($d_h/d$ = 0.00139 and 0.00278) and open areas up to 23% increased the damping ratios to an average value of 0.15 while maintaining a frequency corresponding to the solid wall sector tank. Above 23% open area, the results become inconsistent in frequency and damping ratio.

Test results for the 60° sector tank with perforation hole ratios = 0.0056 are presented in Figure 10. From these results, it can be seen that increased damping ratios at frequencies corresponding to the solid sector wall exist only for perforated sectors of 8 to 16% open area, depending on the excitation amplitude. Additional tests with smaller perforation ratios ($d_h/d = 0.00139$ and $0.00278$) yielded mean damping ratios of approximately 0.12 at 16 to 23% open sector area, depending on excitation amplitude. The lower percent open area corresponds to the lower excitation amplitudes. Figure 11 presents similar data for the 90° sector tanks. It can be seen that sectors with perforation ratios $d_h/d = 0.0056$ lose their compartmentation effect at small excitation amplitudes; however, tests with sector walls having perforation ratios of $d_h/d = 0.00139$ and 0 00278 and up to 30% open area produced mean damping ratios of 0.12 at frequencies corresponding to the solid sector wall for translational excitation amplitudes of $x_o/d = 0.00417$ and $0.00833$. Tests at excitation amplitudes $x_o/d < 0.00417$ corresponded to results similar to the solid sector for perforated walls with a hole ratio $d_h/d = 0.00139$. The results for the perforated sector wall with a hole ratio $d_h/d = 0.00279$ were inconclusive and no consistent damping ratios or resonant frequencies were obtained.

## CONCLUSIONS

Compartmenting of cylindrical tanks with solid walls as a means of increasing the lowest resonant frequency above that of uncompartmented cylindrical tanks can be realized. The experimental resonant frequencies appear to agree closely with the theoretical values only at small values of translational excitation amplitudes; for large values of translational excitation amplitude, a significant decrease in resonant frequency exists. The liquid damping ratio with these solid wall sector tanks averaged approximately 0.04.

Compartmenting of cylindrical tanks with perforated walls retains the compartmented resonant frequency response better for the larger translational excitation amplitudes. The tank with 45° sectored walls maintains the compartmented resonant frequency through a larger range of perforation hole sizes and percent of open areas. However, for lower amplitudes the resonant frequency decreased to a value which approximated the resonant frequency of an uncompartmented cylindrical tank for the three sectored configurations. At the compartmented resonant frequencies, the liquid damping ratios were about 0.08 to 0.1. When the resonant frequencies approximated those attained in the uncompartmented tank, the liquid damping ratios increased to a range of 0.08 to 0.2.

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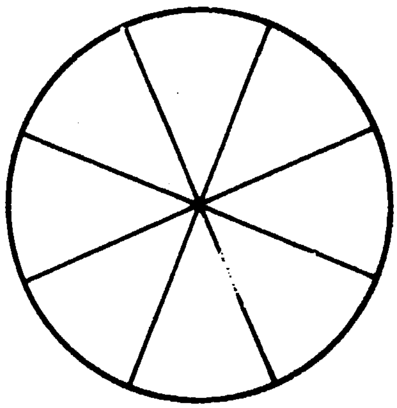
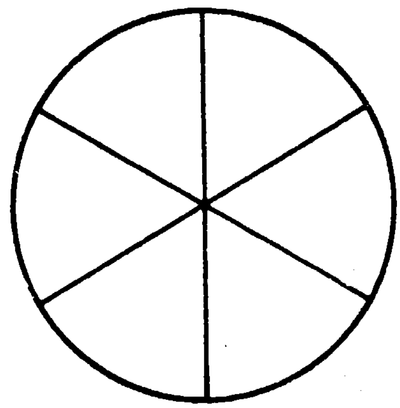


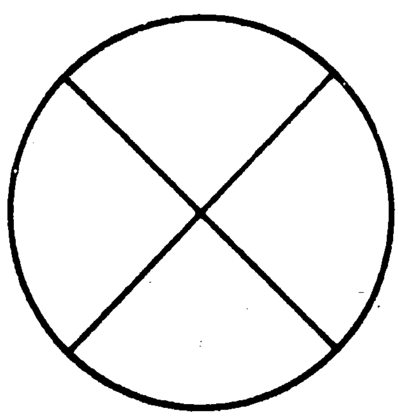
45° SECTOR

$X_o$



60° SECTOR

$X_o$



90° SECTOR

$X_o$

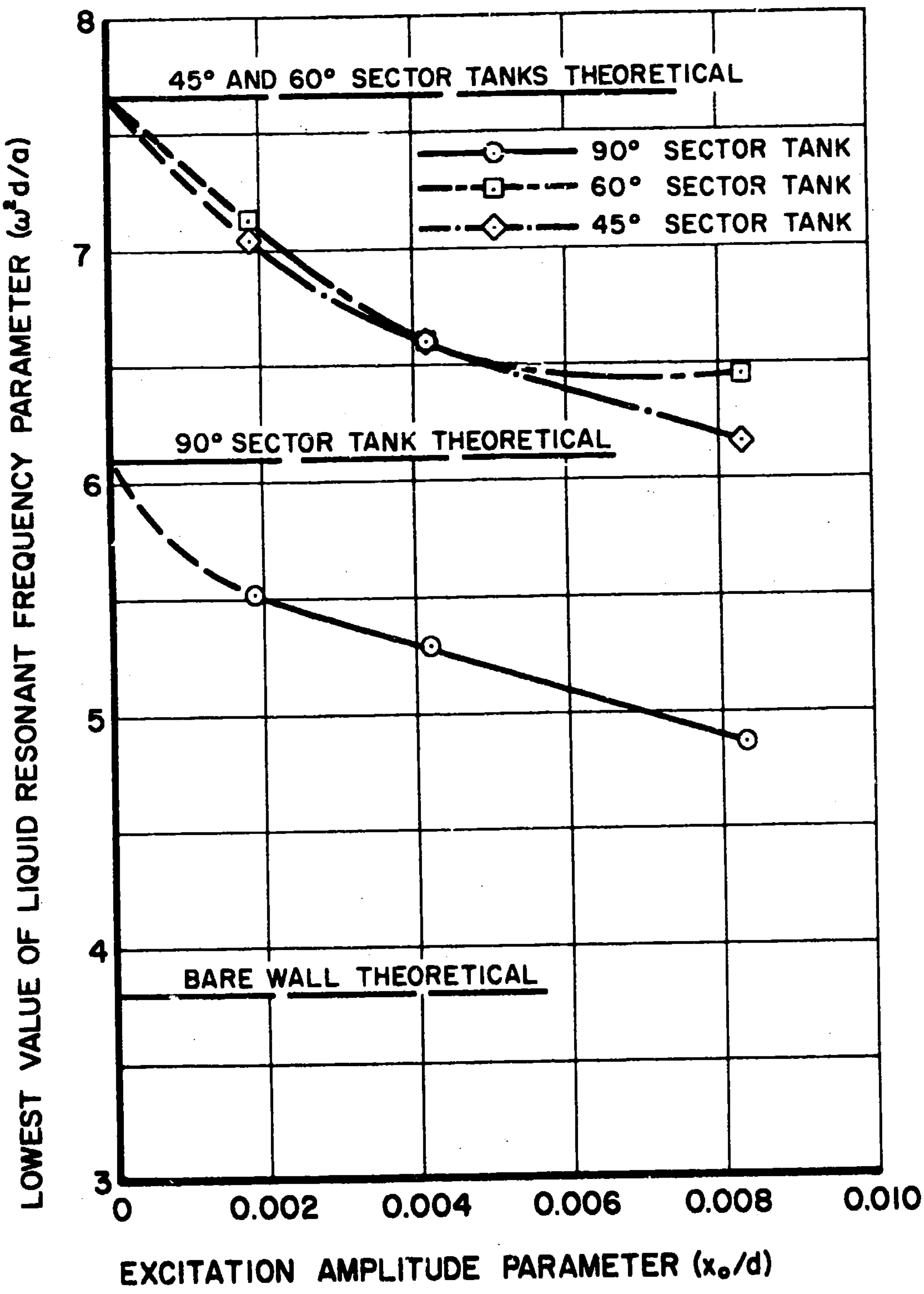



FIGURE 2. EFFECT OF EXCITATION AMPLITUDE ON THE LOWEST RESONANT

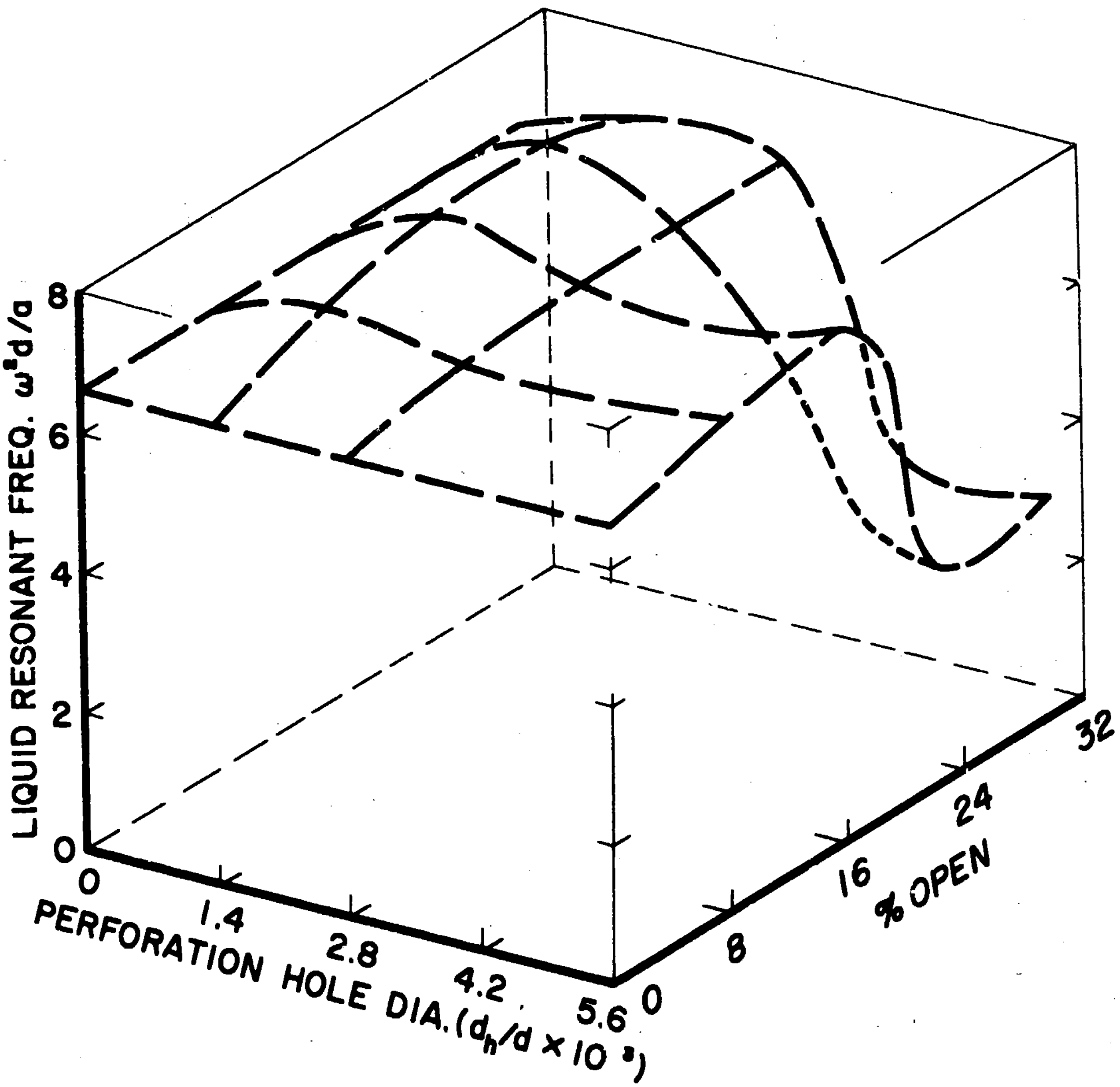



FIGURE 3. EFFECT OF PERFORATION HOLE SIZE AND PERCENT OPEN AREA ON THE LIQUID RESONANT FREQUENCY FOR A 45° SECTOR TANK

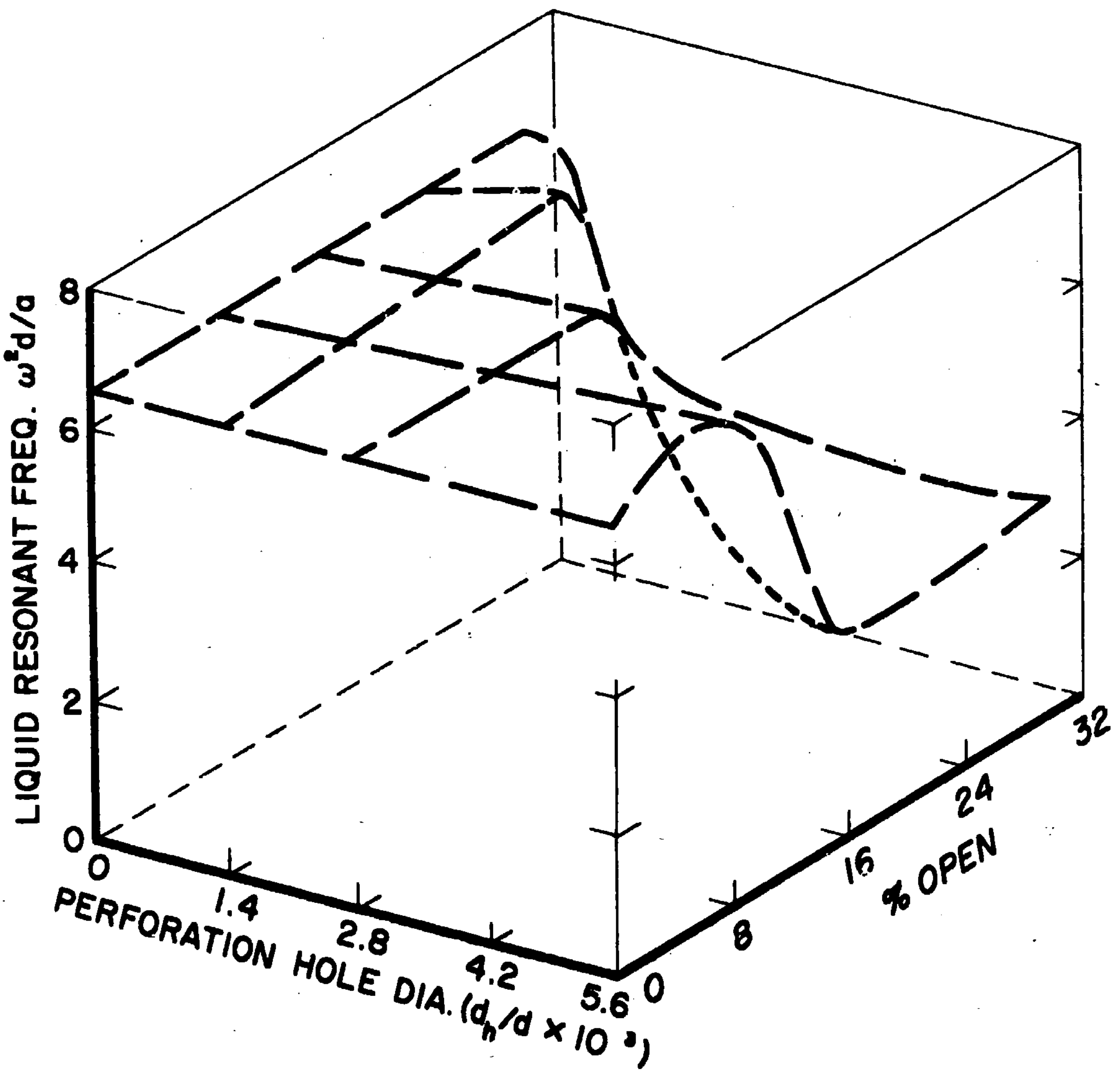



FIGURE 4. EFFECT OF PERFORATION HOLE SIZE AND PERCENT OPEN AREA ON THE LIQUID RESONANT FREQUENCY FOR A 60° SECTOR TANK

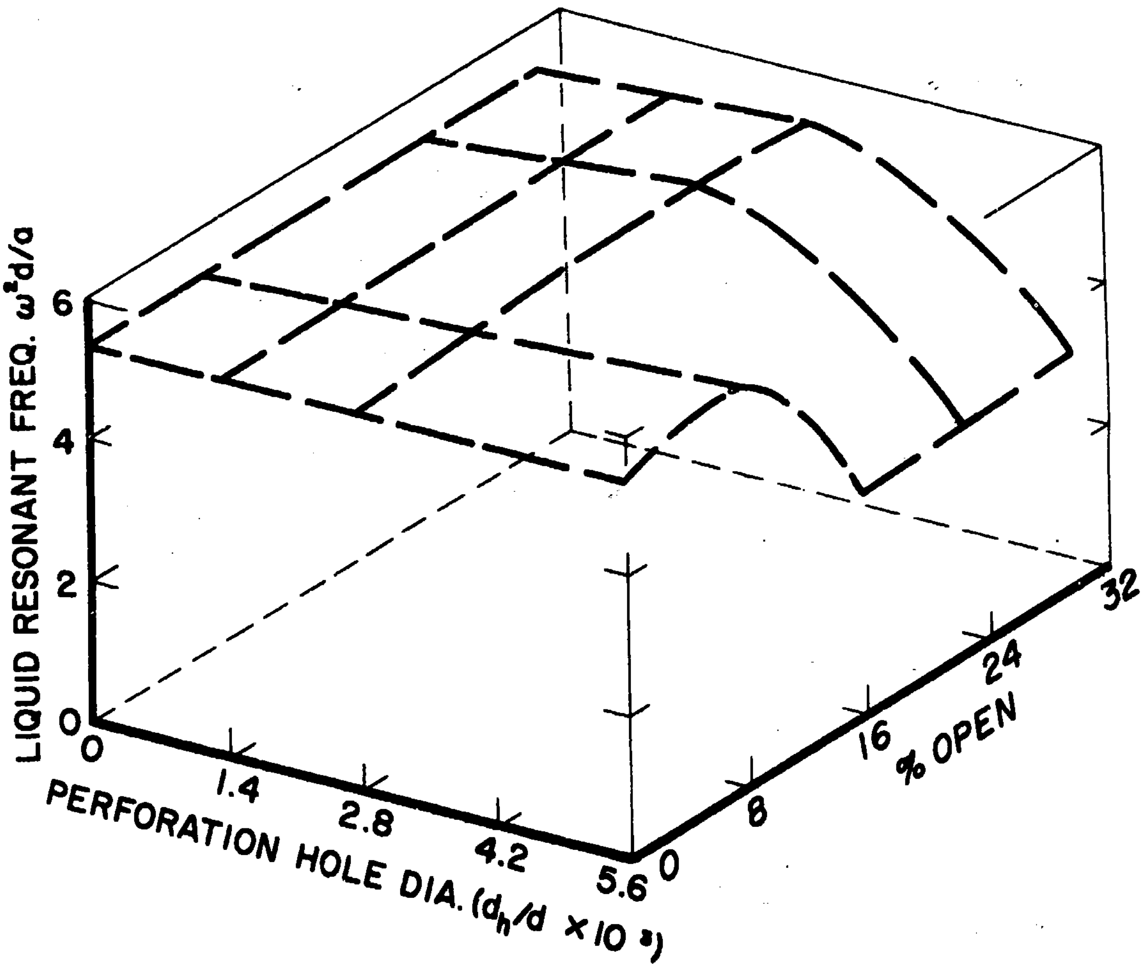



FIGURE 5. EFFECT OF PERFORATION HOLE SIZE AND PERCENT OPEN AREA ON THE LIQUID RESONANT FREQUENCY FOR A 90° SECTOR TANK

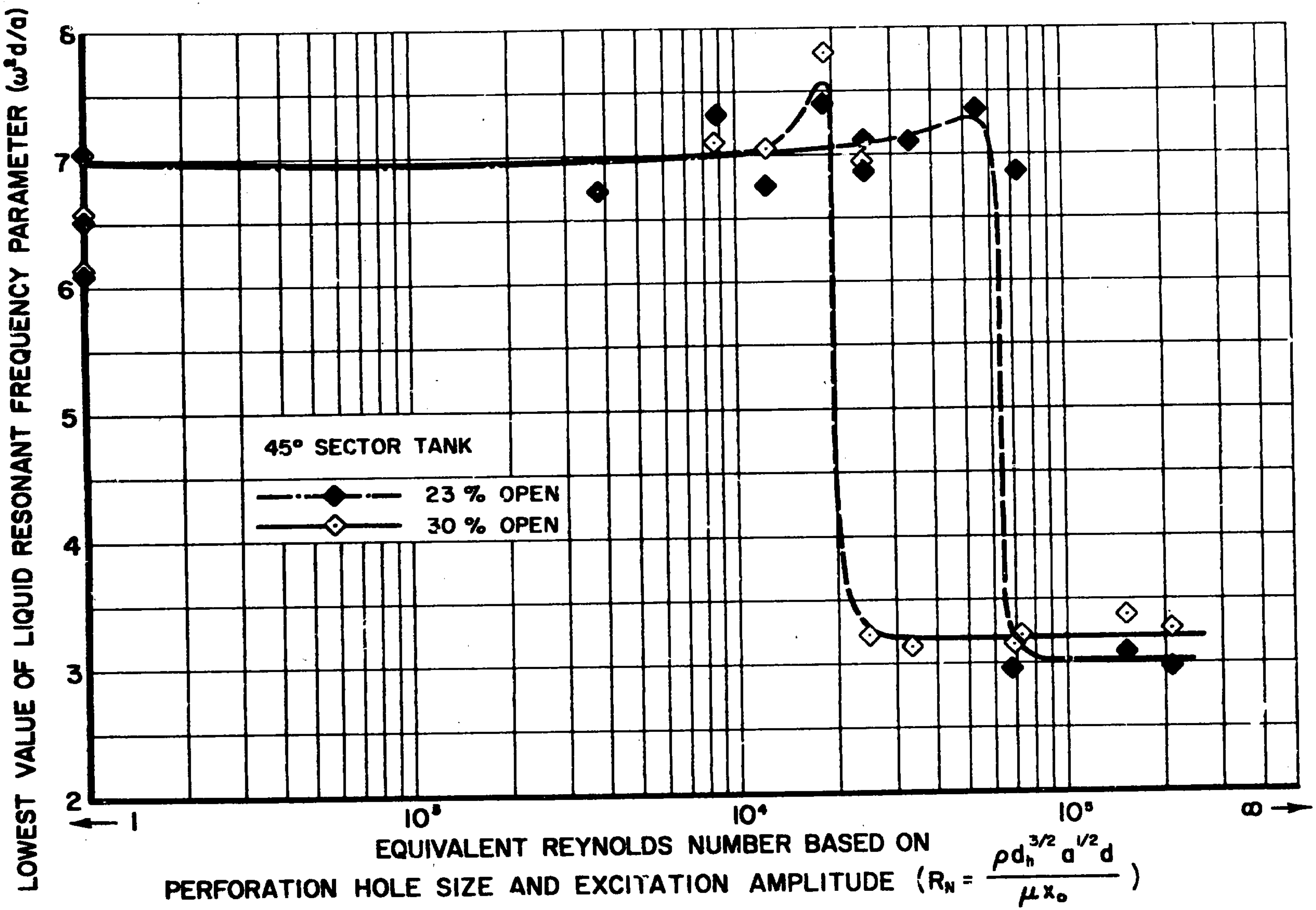



FIGURE 6. VARIATION IN LOWEST LIQUID RESONANT FREQUENCY WITH REYNOLDS NUMBER-45° PERFORATED SECTOR TANK

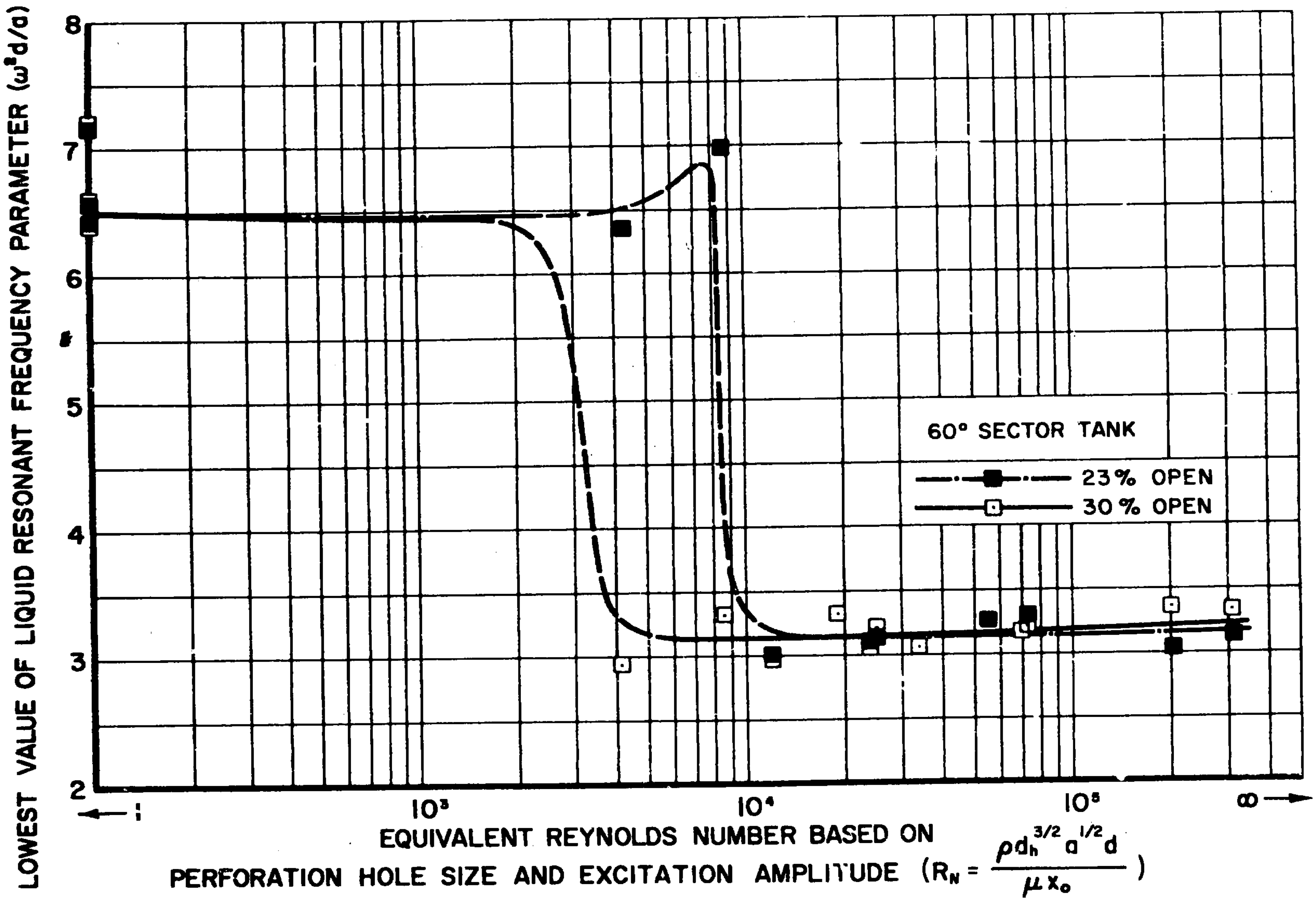



FIGURE 7. VARIATION IN LOWEST LIQUID RESONANT FREQUENCY WITH REYNOLDS NUMBER-60° PERFORATED SECTOR TANK

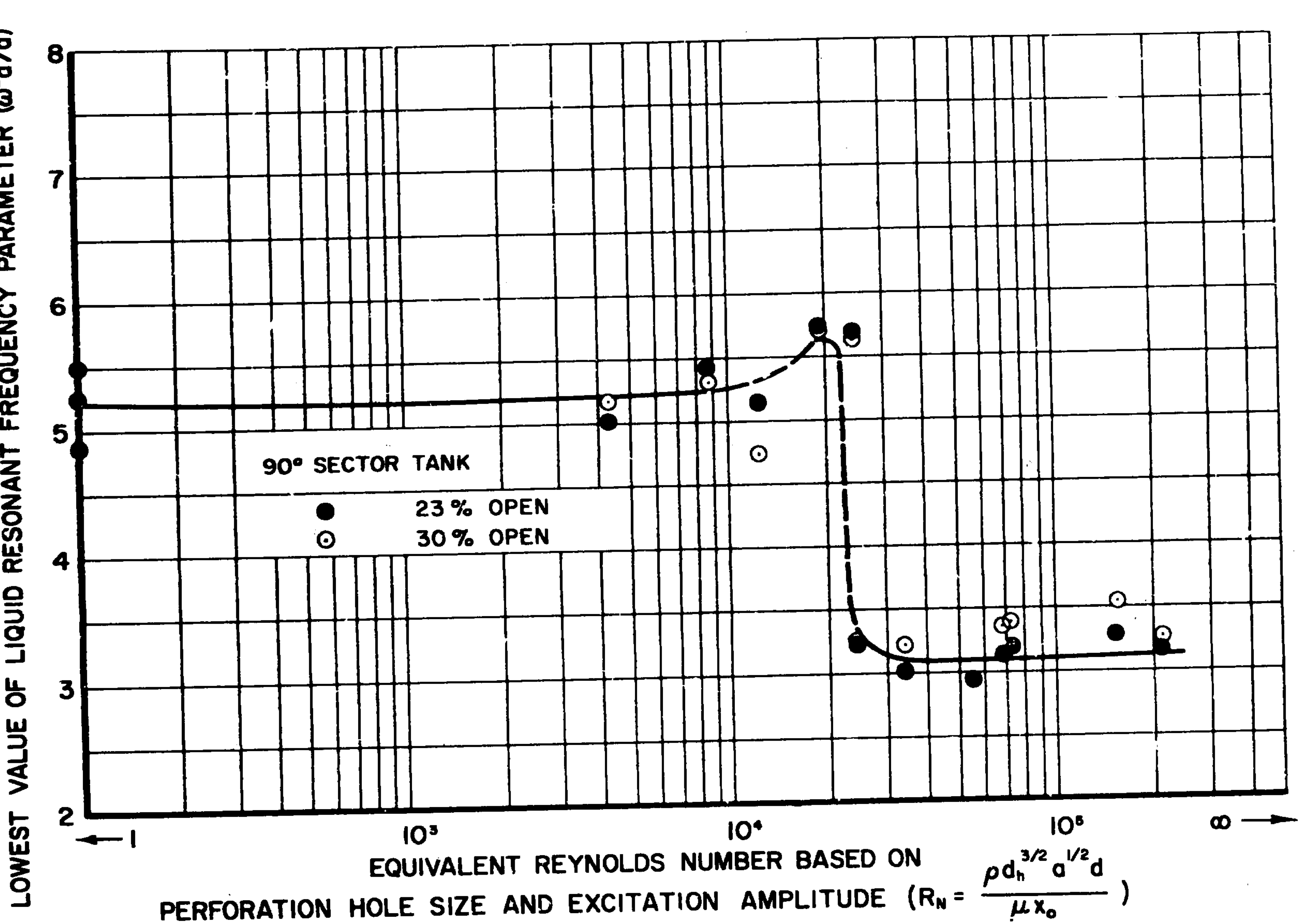



FIGURE 8. VARIATION IN LOWEST LIQUID RESONANT FREQUENCY WITH REYNOLDS NUMBER-90° PERFORATED SECTOR TANK

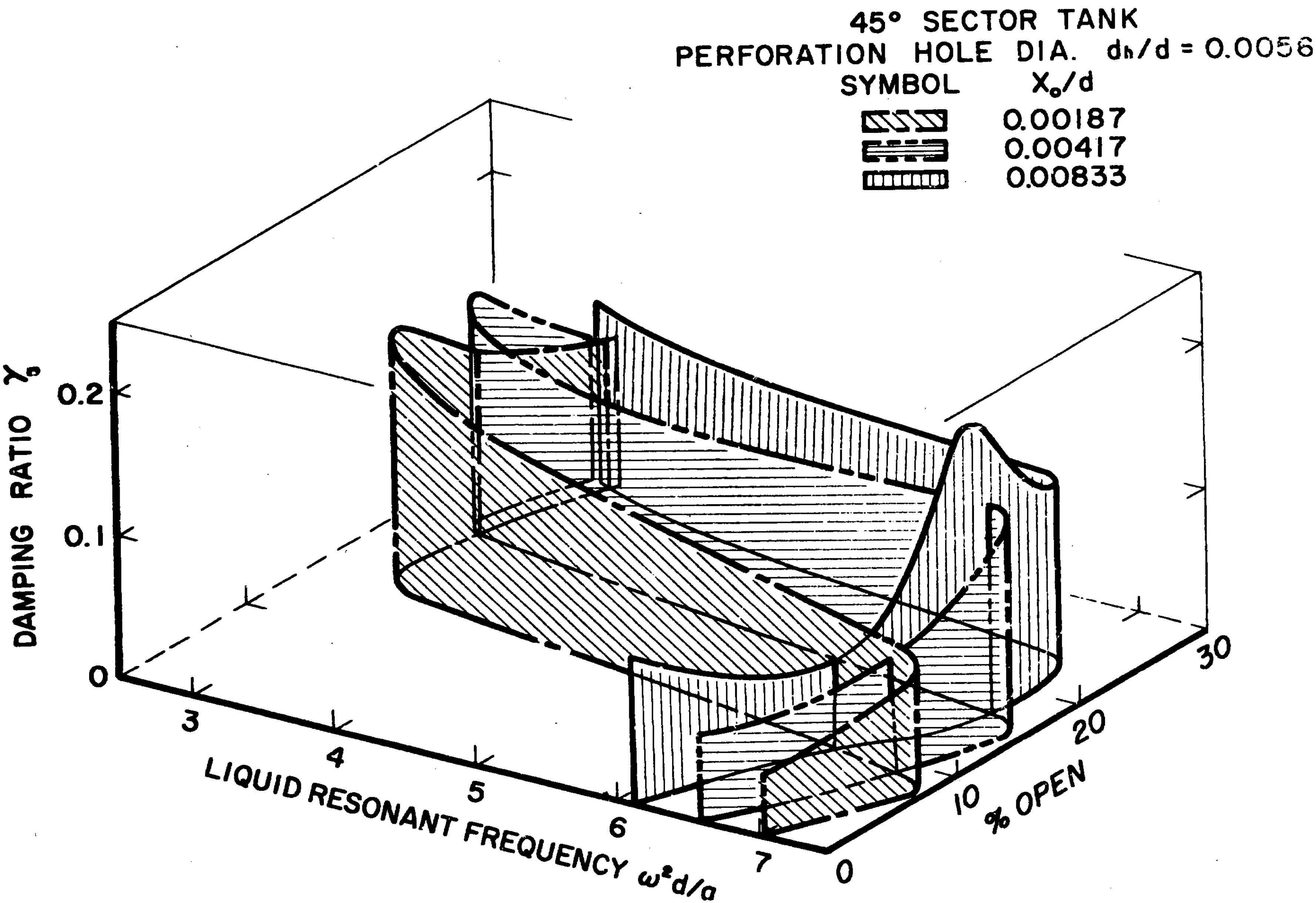



FIGURE 9. VARIATION IN DAMPING RATIO FOR 45° SECTOR TANK

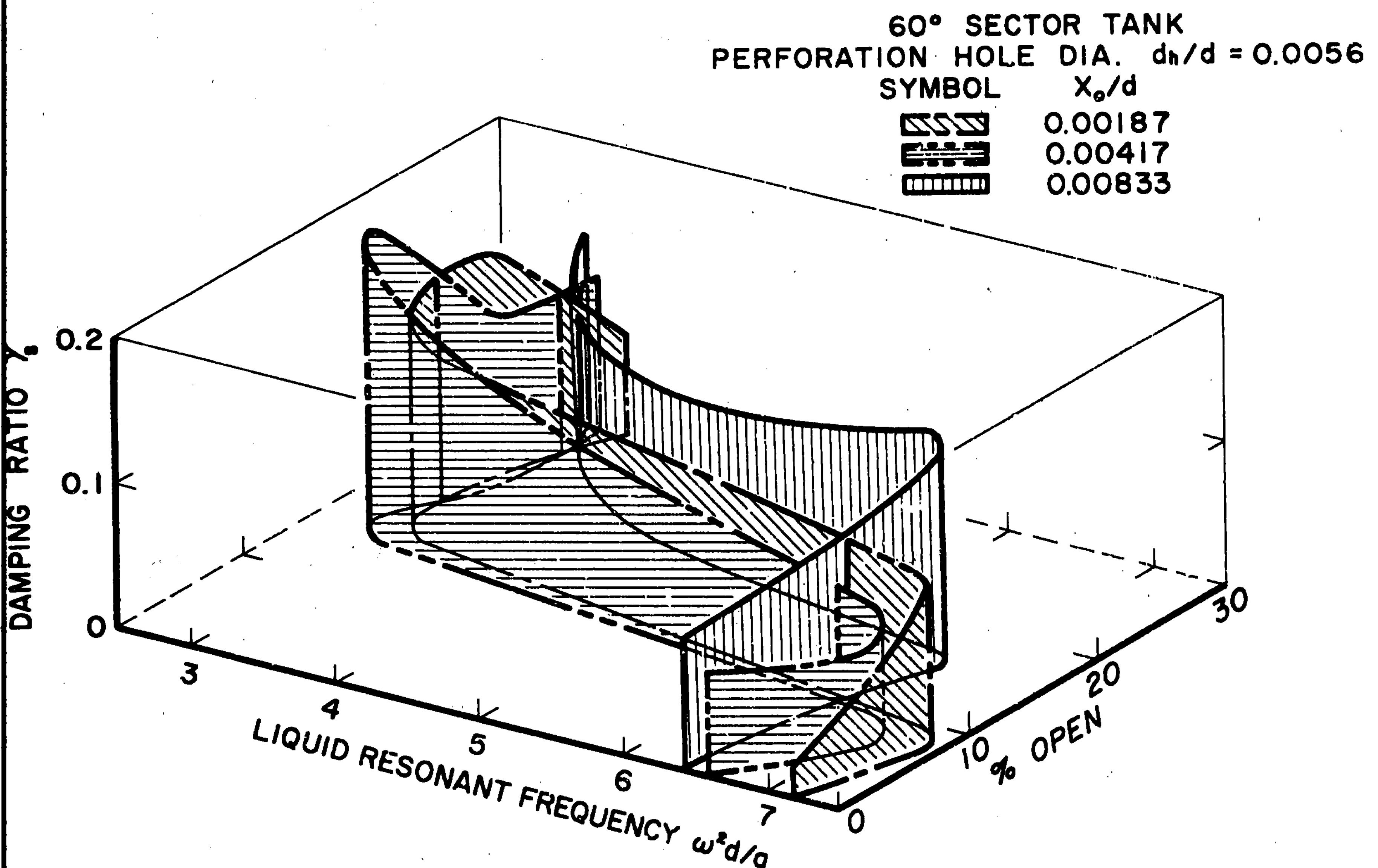



FIGURE 10. VARIATION IN DAMPING RATIO FOR 60° SECTOR TANK

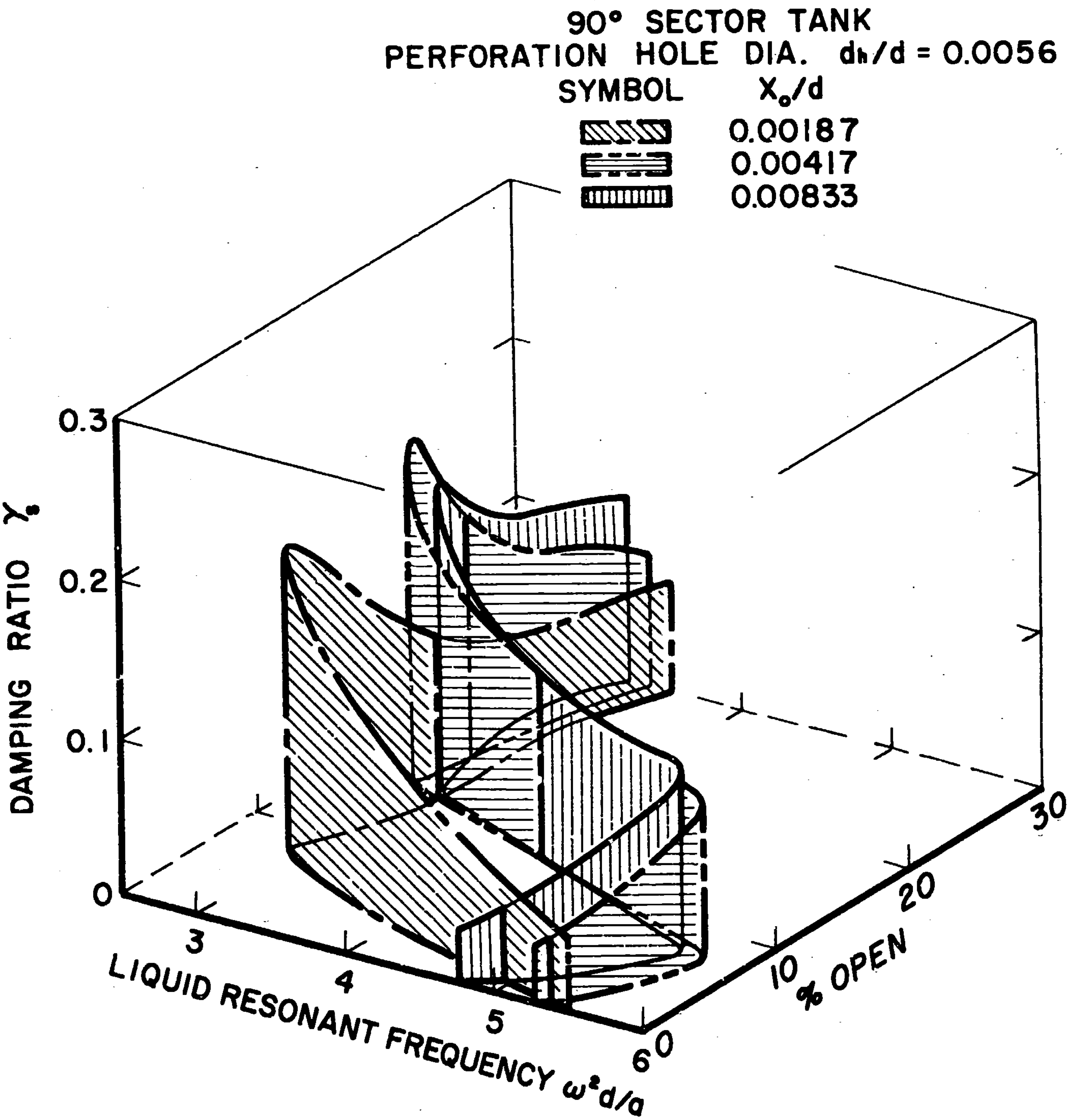



FIGURE 11. VARIATION IN DAMPING RATIO FOR 90° SECTOR TANK